Appendix I

Climate Scenarios for a California Energy Commission Study of the Potential Effects of Climate Change on California: Summary of a June 12-13, 2000, Workshop

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1. Introduction

Climate is a central factor in California life. It is at least partially responsible for the state's rapid population growth in the past 50 years, and largely responsible for the success of industries such as agriculture and tourism. California's climate is quite variable, differing widely from coastal regions of the state to the interior valleys and into the Sierra Nevada. It is also extremely variable from year to year. Historic records suggest that variations in precipitation by a factor of three from one year to the next are not unusual.

It is in this context that we consider the potential effects of human-induced climate change on the state. Climate change has been studied widely at the international, domestic, and state levels. Previous studies that focused on California have suggested that climate change could result in changes not only in temperature but also, and perhaps more important, in water supply, flooding frequency and intensity, crop yields, and sea level. In addition, climate change could affect the strength of weather phenomena that often have adverse impacts on California, such as the El Niño/Southern Oscillation (ENSO; see, for example, recent studies by the Union of Concerned Scientists [Field et al., 1999] and the U.S. National Assessment of Climate Change [NAST, 2000], as well as the 1991 monograph entitled *Global Climate Change and California: Potential Impacts and Responses,* by Knox and Scheuring [1991]). Given the importance of climate to California and the potential effects of climate change identified in the literature, it is critical that the state develop information to better understand the potential impacts of climate change and strategies for managing these risks.

Consequently, the California Energy Commission (Commission) — as part of its Public Interest Energy Research (PIER) program — conducted a major study of the potential impacts of climate change on California and the effectiveness of potential adaptation responses. This study, which was coordinated by the Electric Power Research Institute (EPRI), examined climate change implications for the state's water supplies, agriculture, coastal areas, vegetation, timber, and energy supply and demand.

Identifying different climate change scenarios is a key component of any study on climate change impacts. Estimates of past, present, and future regional change in climate are uncertain, so it is not currently possible to specify reliable predictions of climate change on scales the size of states or counties (Houghton et al., 1996; Wigley, 1999). Because of this uncertainty, it is necessary to construct *scenarios* of regional climate change (Smith and Hulme, 1998). These scenarios *should not be interpreted as actual predictions of climate change*. Instead, scenarios are used to better understand how ecosystems such as vegetation and water resources could be affected by changes in climate.

A workshop was held June 12-13, 2000, to discuss the options for scenarios and to use that discussion to select a limited set of scenarios for analysis in this project. Members of the project team, leading climate scientists, other California climate change researchers, and state government officials attended the workshop, which was held in Sacramento, California, at the Commission offices. The workshop attendees addressed possible options for developing scenarios (e.g., from regional climate models, statistical downscaling, or historic analogs), agreed on the general characteristics of a useful set, and specified a set of scenarios to focus the analysis.

This appendix summarizes the workshop and presents the scenarios that the participants chose for impact analysis. The workshop agenda and a list of attendees are included as Attachments A and B.

2.   Workshop Objectives and Structure

▸   The workshop objective was to develop a set of climate change scenarios to drive analyses of the potential impacts of climate change on California, *not* to develop actual predictions of climate change for the state. To frame the discussion, Guido Franco, contract manager for the Commission, Tom Wilson, project manager for EPRI, Chuck Hakkarinen of EPRI, and Joel Smith of Stratus Consulting outlined desirable characteristics for the climate change scenarios, saying that the scenarios should: Provide estimates of changes in climate variables used as inputs into the impact models at a sufficiently fine spatial and temporal scale for use by the models.

▸   Be limited in number to meet project time constraints. Because the impact analyses were scheduled to begin in the summer of 2000, scenarios that could be available by midsummer of that year were necessary. For this reason, selecting climate change scenarios that would take months or more to develop was inappropriate.

▸   Be physically plausible. This means that changes in climate variables need to be physically consistent with "first principles" of meteorology. For example, a California climate change scenario that includes both increased solar radiation and increased precipitation would not be considered "physically plausible," because decreased cloud cover is unlikely to be associated with increased precipitation.

▸   Be consistent with global projections of climate change. In nearly all climate models, temperatures and precipitation are projected to rise at a global level. However, changes in regional variables, particularly precipitation, could deviate quite substantially from the global mean changes.

▸ Reflect a plausible range of change in key variables such as temperature and precipitation. This is a critical criterion. The scenarios needed to reflect the approximate bounds of regional climate change so that they would convey uncertainties about regional climate change. If the scenarios were to reflect a range that was too narrow — for example, showing only precipitation increases when precipitation actually decreases under some model projections — they could have proved to be misleading

The workshop agenda was designed to review alternative approaches and sources of information for developing scenarios before making choices. The key elements of the workshop (as detailed in Attachment A) were:

▸ **Impact modelers' needs.** Determine the climate scenario data needs for each of the modelers of impacts.

▸ **Key drivers of California's climate.** Review the drivers of the past and present California climate, including determinants of seasonal and interannual variability.

▸ **Evidence from climate models.** Examine the availability of data from climate models, including general circulation models (GCMs) and regional climate models (RCMs), for use in developing climate change scenarios for California.

▸ **Statistical downscaling.** Review attempts to use statistical downscaling from climate models in California and other considerations for creating high-resolution climate change scenarios in the state.

▸ **Regional climate modeling in California.** Review current research efforts on modeling of climate change in California.

▸ **Considerations when choosing scenarios.** Review desirable characteristics of climate scenarios for the project.

▸ **Scenario identification.** Develop a set of climate change scenarios for California for use in the impact models, based on the insights from the earlier discussions.

For each of these elements, except the last one, climate scientists or impact researchers were invited to give short (15-20 minute) presentations. Each presentation was followed by considerable discussion. However, because of the desire to expedite the meeting scheduling and to encourage frank and open discussions, no papers were explicitly solicited for the workshop and no proceedings, other than this summary report, will be published.

Commissioner Robert Laurie, Commissioner Arthur Rosenfeld, and Kelly Birkinshaw (Director of Energy-Related Environmental Research under the PIER program) launched the workshop and welcomed all participants. They emphasized the importance of the climate issue and of this study for the state of California.

3. Impact Modelers' Needs

The following researchers with expertise in impact studies attended the workshop and presented their needs for climate change scenario data[1]:

Researcher   *Topic*

Ron Neilson, U.S. Forest Service/Oregon State University   *Vegetation*
Dr. Neilson discussed estimation of changes in location of vegetation in California under alternative future climate scenarios. His model has a spatial resolution of 10 km and considers 45 classes of vegetation.

John Dracup, University of California, Berkeley   *Hydrology*
Norm Miller, Lawrence Berkeley National Laboratory
Dr. Dracup and Dr. Miller discussed estimation of changes in runoff in representative river basins in the state. Their output fed into the work on water resource management, which was conducted by Dr. Lund.

Jay Lund, University of California, Davis   *Water Resources*
Dr. Lund discussed using CALVIN (California Value Integrated Network) a detailed model of California's water management system, to examine how changes in water supply could be allocated in the state. CALVIN allocates water to the highest (economic) value uses, but can also be run to reflect current water appropriations and reservoir operating rules. CALVIN needs runoff information, which was supplied by Drs. Dracup and Miller. (At the time of the workshop, Dr. Lund was enhancing the CALVIN model to include a much better representation of hydroelectric facilities.)

Richard Howitt, University of California, Davis   *Agriculture*
Dr. Howitt addressed the use of SWAP, a model of California agriculture, to estimate changes in crop production patterns in the state in response to changes in land availability, crop yields, and water supplies. Yields and water supplies may be directly affected by climate change inputs to the model.

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1. In addition, a study of coastal impacts from sea level rise was conducted. That study used eustatic sea level rise scenarios of 33, 67, and 100 cm by 2100.

Robert Mendelsohn, Yale University   *Timber, Energy*
Dr. Mendelsohn discussed using estimates of changes in vegetation (obtained from Dr. Neilson) to examine potential impacts on California's timber industry. The climate scenarios could then be used to assess the potential sensitivity of the energy sector to climate change.

After the individual presentations, all the participants discussed specific climate variables that would be needed as inputs to the impact studies, along with their preferred spatial and temporal resolutions. To summarize this information, several tables were developed during the workshop. Table 1 displays the climate variables that the participants decided the studies would need.

Table 2 presents the desired spatial and temporal resolution of data that the impact models would need from the climate models.

The participants noted that, at a minimum, monthly changes in the six variables would be needed. These changes in monthly average conditions would then be combined with an observed database (preferably at least 30 years long) to yield a "simplified" scenario that adjusts observed (daily or more frequent) climate by modeled changes in monthly average climate. This would produce a climate change scenario with sufficient temporal resolution for impact models.

Table 1. Climate variables needed for each study

Climate variables	Studies			
	Vegetation	**Hydrology**	**Agriculture**	**Energy**
Minimum temperature	✓	✓	✓	✓
Maximum temperature	✓	✓	✓	✓
Precipitation	✓	✓	✓	✓
Vapor pressure	✓			
Wind speed	✓			
Radiation	✓	✓		

Table 2. Desired spatial and temporal resolution for climate variables

Climate variables	Studies			
	Vegetation	**Hydrology**	**Agriculture**	**Energy**
Spatial resolution	10 km	30 km	26 regions	County level
Temporal resolution	Daily (3 h)	Daily (6 h)	Daily	Monthly

Note: numbers in parentheses are the highest desired resolution.

4.   Key Drivers of California's Climate

To set the baseline for assessing climate change, presentations were given on key drivers of California's current climate. Marlyn Shelton of the University of California, Davis, identified current climate data sources, recent trends in California's climate, and the general circulation drivers of California's climate. Dan Cayan of the Scripps Institution of Oceanography presented some of the key drivers of interannual variability in California's climate.

The key data sources for California climate include:

▸   U.S. Historical Climatology Network
(http://cdiac.esd.ornl.gov/epubs/ndp019/ndp019.html). The U.S. HCN has 54 stations, 20 of which have precipitation data. The data have been modified to remove stations with biases.

▸   Western Regional Climate Center (http://wrcc.sage.dri.edu/). This data source has 184 stations.

▸   California Data Exchange Center (http://cdec.water.ca.gov/). The CDEC has 500 stations and measures snow depth and water content.

▸   National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR; "Reanalysis;" http://www.ncdc.noaa.gov/ol/climate/climatedata.html). The data are put on a 2.5-degree grid.[2]

Changes in California's climate in the 20th century were not consistent across the state. For example, while Redding cooled, Davis and Pasadena warmed. There was an apparent warming in the spring in northern areas, with as much as a 2°C (4°F) warming observed in some northern areas. Although Eureka, Sacramento, and San Diego experienced little change in precipitation, the northern Sierras saw an increase. One clear trend was a reduction in snow water content, particularly in April (see Figure 1).

A key determinant of the seasonality of California's climate is the location of the subtropical high-pressure system in the eastern Pacific Ocean and its migration north and south during seasons and between years. When the subtropical high moves farther south (in the winter and often in El Niño years), the resulting position of the jet stream enhances the probability of Pacific storms striking the California coastline. Migration of the subtropical high farther north (in the summer and often in La Niña years) tends to reduce the probability of winter storm landfall in

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2. Such gridded data may be appropriate for comparing observations with GCM estimates of current climate.
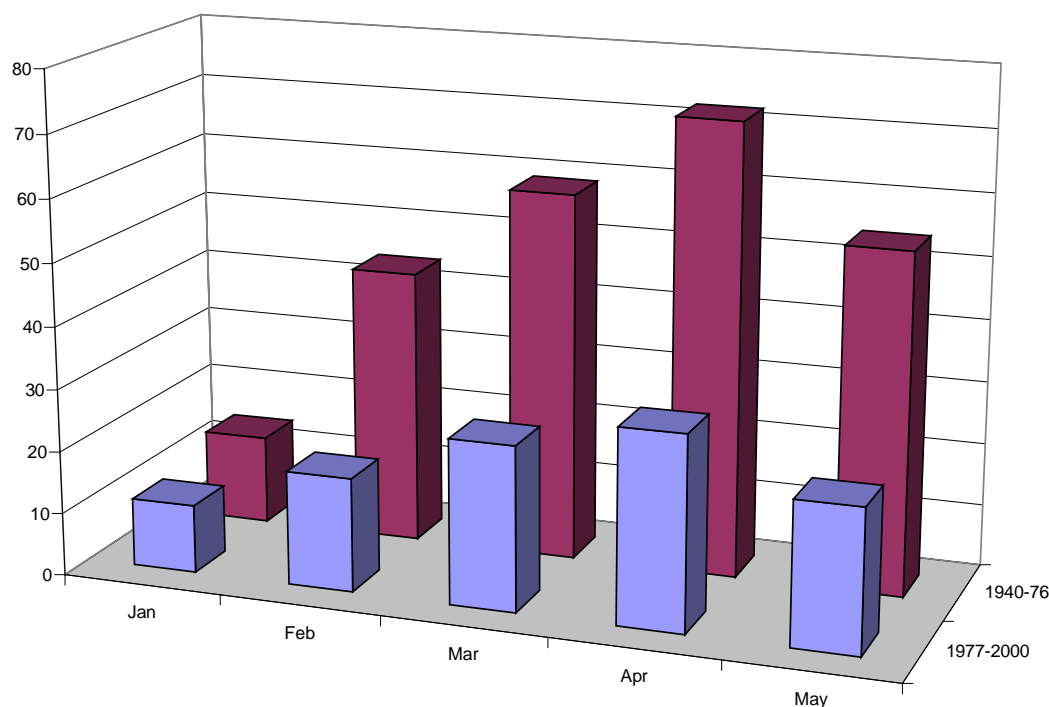
Figure 1. Monthly average snow water content (inches) in the Sierra Nevada Mountains measured at Echo Summit, California, 1940-2000. Monthly averages for the years from 1977 to 2000 are substantially lower than the years from 1940 to 1976.

California. The positions of the subtropical high appear to be strongly influenced by very large-scale climate factors that extend across much of the Pacific Basin. Global warming is unlikely to change this critical feature of California's climate.

Ocean circulation also plays a major role in influencing year-to-year variation in California's climate. Cool ocean water in the Pacific current along the coastline suppresses both air temperatures and evaporation near the coast. Two key drivers of California's interannual climate variability are the ENSO and the Pacific Decadal Oscillation (PDO). The El Niño condition arises when the eastern Pacific surface waters near South America warm. This condition, which tends to occur every 3 to 5 years and usually lasts about 12 to 18 months, can alter global weather patterns. Statistical studies of El Niño occurrences during the last century show that they often result in warmer temperatures in California (mostly in the winter) and a southerly shift of the extratropical jet stream. This often brings more winter precipitation into southern California than average. For example, the 1997-1998 El Niño, which was one of the strongest on record, brought several extreme precipitation events into southern California. These events, combined

with denuded hillsides from previous seasonal wildfires, resulted in significant flooding and mudslides. The warm and wet conditions often associated with El Niño may also increase the presence of mosquitoes and molds.[3]

La Niña, the "opposite" climate state to El Niño, is characterized by cooler than normal sea surface temperatures in the eastern tropical Pacific Ocean. The winter Pacific storm tracks in La Niña years tend to be farther north, producing more precipitation in Oregon and Washington and less precipitation in California. However, the general tendencies in temperatures and precipitation associated with El Niño and La Niña do *not* always hold true. For example, some of the wettest winter seasons (in terms of total winter precipitation) in northern California have occurred in La Niña years. And although significant flooding has often occurred in southern California in El Niño years, a major flood was never recorded in northern California in an El Niño year during the 20th century.

In contrast to ENSO, the PDO fluctuates on a 20- to 30-year cycle, involving either warming (warm phase) or cooling (cold phase) of waters in the North Pacific Ocean. Warm PDOs have been correlated with increased fishery productivity off Alaska and decreased productivity off the west coast of the lower 48 states. Cold PDOs have yielded the opposite effect. A warm phase of the PDO is believed to have begun around 1977 and may have ended in the mid-1990s. Although some studies have correlated ENSO with climate change (e.g., Trenberth and Hoar, 1996), the PDO has not been correlated with climate change. Given its long periodicity, few scientific observations of full PDO cycles have been possible to date, and its mechanisms of formation and evolution are poorly understood.

5.   Overview of Potential Climate Change: What Do the Climate Models Tell Us?

After discussing the key drivers of current climate in California, workshop participants turned their attention to model projections for climate change induced by increased greenhouse gas concentrations. GCMs are currently the primary source of information used to project future climate change on global scales. In recent years, the use of RCMs has grown, and statistical downscaling has been used to generate estimates of climate change on finer spatial scales (i.e., less than 250 km) than the current generation of GCMs can produce. The potential applicability of GCMs, RCMs, and statistical downscaling to creating climate change scenarios for California was discussed in the next sessions of the workshop.

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3. In a related study (Appendix XIV), EPRI examined changes in hospital admissions in California during El Niño episodes.

5.1   General Circulation Models

Tom M.L. Wigley of NCAR in Boulder, Colorado, presented an overview of the changes that current GCMs project for California climate, focusing on temperature and precipitation. Dr. Wigley first addressed how well the models do in estimating current climate around the world, particularly how well they simulate the mean average climate, climate variability, the relationship among climate variables, and key climate mechanisms. It is often argued that the better the models do at simulating current climate, the more confidence we might have in their predictions of future climate. One difficult variable for the GCMs to simulate consistently and reliably is precipitation. In estimating the global spatial pattern of precipitation, the most accurate models are estimating only half of the observed spatial pattern of precipitation correctly. There are some indications that the more recent versions of models are improving in their simulations of current climate. Among the more than 30 GCM scenarios available, the Hadley Centre (United Kingdom) model appears to have performed best in simulating current precipitation patterns in recent years.

One major shortcoming of essentially all current GCMs is their spatial resolution. Although model resolution has increased by a factor of 2 to 4 in recent years, the best models still have grid boxes of a few hundred kilometers in dimension. In a typical GCM, each grid box contains values for one average elevation and average climate; that is, there is no spatial variation within the grid box. Thus, the GCMs, at current resolution, drastically smooth out most of California's complex topography, which has a major influence on estimates of temperatures and especially precipitation. Moreover, the models do not contain such important terrain features as the Coastal Range, the Central Valley, and the Sierra Nevada. However, model resolution is improving, which may be an important reason why GCM estimates of climate change are improving as well.[4]

Dr. Wigley described his examination of 21 GCM simulations to see what patterns for California climate change emerged from the models. He found that all the models estimated warmer temperatures for the state under assumptions of increased radiative forcing from greenhouse gas emission increases. The degree to which the state warmed seemed to largely depend on the particular model's sensitivity to higher greenhouse gas concentrations. The more sensitive the model, the greater the warming it estimated.

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4. A recent paper on GCMs (Grassl, 2000), however, stated, "The highest spatial resolution of GCMs is still coarse at present (>100 km), and many small-scale processes will remain unresolved for many years to come. Thus impact studies, especially in areas with strongly varying topography or a mix of surface types, are hampered."

Dr. Wigley suggested that one way to look at precipitation changes across different models in a consistent manner is to examine the percentage change in precipitation *per degree Celsius increase in average global temperature*. This technique smoothes differences in model sensitivity to higher greenhouse gas concentrations (i.e., it eliminates the "bias" that some models estimate higher changes in precipitation partly because they estimate greater increases in global average temperature). Interestingly, the 21 models in Dr. Wigley's analysis did not agree on changes in precipitation in California (see Table 3). The model estimates ranged from a 56% *increase* in winter precipitation in the Canadian Climate Centre Model transient run (CCCTR) to a 10% *decrease* in winter precipitation in a Japanese GCM. About two-thirds of the models estimated some increase in precipitation. Based on this, Dr. Wigley concluded that it is more likely than not that winter precipitation in California will increase.

Table 3. Area average precipitation changes (percent change per 1°C global-mean warming)

Grid box central points (5° by 5° grid)
Latitude range is 32.5 to 42.5 N inclusive
Longitude range is -122.5 to -117.5 E inclusive

	Annual	**December-February**	**June-August**
BMRC	-8.0	-6.5	-9.9
CCC	6.9	14.0	3.5
CSIR1	-0.7	-1.8	-1.0
CSIR2	2.6	5.3	-2.7
ECH1	9.8	8.4	2.8
ECH3	-3.2	9.9	-22.5
GFDL	0.0	1.8	-0.1
GISS	2.2	1.5	3.6
LLNL	0.0	1.5	-2.7
OSU	-1.3	0.6	-5.2
UIUC	2.3	0.3	34.7
UKHI	2.6	6.2	-5.2
UKLO	4.1	6.1	-0.2
UKTR	2.9	12.4	0.3
CCCTR	26.3	56.0	7.1
JAPAN	-7.7	-10.7	0.7
CSITR	-2.8	7.7	-10.0
ECH4	-3.1	8.7	-8.1
GFDTR	-0.1	-3.4	-4.6
HadCM2	13.8	23.1	7.8
NCAR	2.1	0.4	7.4
Overall mean	2.3	6.7	-0.2
Standard deviation	7.3	13.2	10.4

Source: Tom M.L. Wigley, NCAR, personal communication, June 21, 2000.

On the whole, the models tended to project a 5% to 10% increase in winter precipitation per degree Celsius warming, with a larger increase in southern California than in northern California. The models did not show a consistent change in summer precipitation and had an average summer precipitation change of about zero. Dr. Wigley concluded that the most likely change for California's climate is an increase in winter precipitation and no change in summer precipitation.

5.2   Regional Climate Models

Dr. William Gutowski of Iowa State University (ISU) presented results from two widely used RCMs, RegCM2 (developed at NCAR) and HIRHAM (developed at the Danish Meteorological Institute). RCMs, which are models of a portion of the earth's surface, have higher resolution than GCMs and are "nested" within a GCM. In this context, nested means that the RCM is run using boundary conditions from the GCM, but it does not provide feedback to the GCM. The RCMs apply the same basic physical equations of motion, energy, and momentum as the GCMs, but because they have higher spatial resolution than GCMs (typically, 50 km or less), they are better able to simulate the effects of topography on weather and climate than GCMs. Computer limitations to date have restricted RCMs to applications over subcontinental regions, for at most a few years of continuous simulation. In contrast, GCMs have been applied globally for simulations spanning centuries or longer. Research efforts with RCMs have focused on improving simulations of current climate for periods of a few months to a few years. A limited set of future climate simulations (10 years or less) are available that are driven by climate change projections generated by GCMs.

Under an EPRI-sponsored project, Dr. Gutowski and colleagues used RegCM2 and HIRHAM to model the western United States at a resolution of 50 km. The RCM simulations were driven by climate change projections from the HadCM2 (Johns et al., 1997), which has a resolution of approximately 300 km. Given their higher spatial resolution, RegCM2 and HIRHAM do resolve much of the topographic variation in California's Coastal Range, Central Valley, and Sierra Nevada. The RegCM2 and HIRHAM have been run so far to simulate (a) the current climate and (b) a future climate (during the 2040s) under increased greenhouse gas and sulfur aerosol conditions.

Of the GCMs Dr. Wigley examined, the HadCM2 model yielded the wettest estimates. Interestingly, RegCM2 and HIRHAM estimated a larger increase in precipitation throughout California than did the HadCM2 model. RegCM2 estimated an increase in temperature of 2°C-3°C (4°F-5°F) over the state, but projected an increase in precipitation of 3-5 mm/day in northern California and 0-1 mm/day in southern California. In contrast, the GCMs projected greater precipitation increases in southern California than in northern California. RegCM2 and HIRHAM estimated changes in winter snowpack water content that varied by location from a 50% decrease to no change.

The ISU investigators have now performed 10-year regional simulations with several regional climate models (Pan et al., 2000). The National Science Foundation cosponsored a major workshop on the subjects in Boulder, Colorado, April 2-4, 2001 (results are available at www.esig.ucar.edu/rcw/index.html). However, no federal agency has initiated a truly major research effort on regional climate modeling, and insufficient time and funds were available under this Commission project to use an RCM to conduct a full transient climate change simulation for the 21st century.

6.   Using Downscaling to Create Climate Change Scenarios for California

Several recent efforts have focused on using sophisticated techniques to create high-resolution scenarios of climate change in California based on the outputs from coarse resolution GCMs. Drs. Sloan and Miller described two of these approaches, which used RCMs, as described earlier in this appendix.

Dr. Wigley presented (on behalf of Drs. Rob Wilby and Michael Dettinger, who were unable to attend the workshop) an analysis of runoff using statistical downscaling. This technique statistically relates local- and regional-scale atmospheric phenomena to large-scale meteorological factors, such as pressure patterns, that are observed in the atmosphere and simulated in GCMs. The technique has the advantage of using large-scale outputs from GCMs that are considered to be more reliable, instead of GCM estimates of regional and local phenomena such as precipitation. The technique assumes that the statistical relationship observed and simulated today between regional/local phenomena and large-scale phenomena would remain similar in the future. It is unknown whether climate change will alter these observed statistical relationships.

Dr. Wigley described the work of Wilby and Dettinger, in which changes in temperature, precipitation, and evaporation patterns derived from HadCM2 GCM simulations were downscaled to appropriate spatial and temporal scales for use as input to the Precipitation Runoff Modeling System (PRMS), which was developed by the U.S. Geological Survey. The PRMS was then used to estimate runoff in the American, Merced, and Carson river basins. The model performs relatively well in simulating observed runoff. With the HadCM2 model driving the changes, the PRMS estimated that there would be large increases in extreme runoff events in the winter for the American and Carson rivers and in the spring for the Merced River.

One difficulty in using downscaling to create scenarios is that the method is site specific, so applying downscaling to create climate change scenarios for the whole state of California could be time consuming. It was judged that insufficient time would be available in the current project to apply downscaling methods across the whole state.

7. Current Activities and Plans for Regional Climate Modeling in California

Three presentations were given on current efforts to model California's climate.

Lisa Sloan from the University of California at Santa Cruz described a regional climate model being developed for California. The model is based on the regional climate model MM4 and was calibrated using 1968-1988 data. Dr. Sloan said that the model would also be used to study changes in mean climate and variability. (It was recently run using 40 km resolution, and the results were published as Snyder et al., 2002.) The model is used mainly to simulate climate of the Holocene, and the effects of anthropogenic increases in greenhouse gas concentrations.

Dr. Cayan described the California Applications Program (CAP), which is funded by the National Oceanographic and Atmospheric Administration (NOAA). CAP examines how climate forecasts are used for fire prevention, water management, and human health, among other purposes. The program also works with managers at the federal, state, and local level to assess how climate forecast information can be provided to users to better meet their needs.

Norm Miller from the Lawrence Berkeley National Laboratory and his colleagues have developed a mesoscale atmospheric model for the Southwest. The model was recently used to examine potential changes in runoff in the American and Russian rivers, using the HadCM2 as the driver of the regional model. The mesoscale model is also being used in a number of ongoing efforts, including a U.S. Environmental Protection Agency Star Grant to examine climate change impacts on the San Joaquin River (with John Dracup and Jay Lund) and the California regional study for the U.S. National Assessment on Climate Change (with Robert Wilkinson of the University of California at Santa Barbara). The model looks at impacts such as changes in the snow line, snow-water equivalents in the snowpack, landslides, water quantity and quality, and hydropower production.

8. Considerations for Creating Climate Change Scenarios for California

Two presentations covered some general considerations that the workshop participants should take into account when developing climate change scenarios for California. Dr. Hakkarinen presented a summary of the draft chapter on climate change scenarios from the Intergovernmental Panel on Climate Change's Third Assessment Report (McCarthy et al., 2001). The report suggests a number of criteria to use in developing or selecting climate change scenarios, including plausibility of the scenarios, consistency with global forecasts of climate change, reflection of a reasonable range of potential regional climate change, and appropriateness for use in impact analyses (i.e., having sufficient spatial and temporal resolution as well as the appropriate meteorological variables).

Dr. Miller discussed the components of regional climate change scenarios. One key issue is resolution, which he said should be no larger than 30 km across. Some models need monthly data; others need daily data.

In reaction to introductory presentations about the desired number of scenarios, Dr. Miller said that fewer than six scenarios would be needed if only *mean* climate changes are to be assessed. However, assessing only mean climate changes would result in information on changes in extreme events being lost. He also mentioned that to do a thorough job of developing scenarios of changes in extreme events, 200 simulated years would be needed — more than what most climate models currently simulate.

Dr. Miller mentioned an e-mail from Stephen Schneider of Stanford University recommending that probabilities be attached to scenarios (see Attachment C). In his e-mail, Dr. Schneider noted that the bigger problem emerging with climate change scenarios is not their technical formulation, but instead how they should be applied. Of particular concern is how to progress from developing plausible scenarios to estimating the likelihood of occurrence of the various components in each scenario. Quantifying the likelihood of outcomes is greatly hampered by the lack of a sufficient number of climate change model runs — both multiple runs (ensembles) with one model and multiple runs with different models of the same scenario — as well as the lack of long-enough observational records to define natural climate variability.

For example, Dr. Shelton noted in his presentation that annual precipitation totals in California can vary by factors of 3 or more between years. Variations in much of the rest of the United States are much less — perhaps varying by at most 50% between years. The causes of such large interannual variations in the natural record are not only poorly understood, but their presence produces large signal-to-noise ratios that reduce the power to detect statistically significant

changes (trends) in climate in both observations and simulations that might be associated with increasing greenhouse gases or other causative factors.

Dr. Schneider urged the workshop participants to attempt to characterize the likelihoods of scenarios — at least qualitatively if not quantitatively. Failure to attempt to do so would only defer the task to the decision makers, who need to use the scenarios but, in Schneider's judgment, are less well equipped to assess their likelihood.

Dr. Miller also mentioned the need to be cognizant of ongoing shortcomings with climate data, such as insufficient sampling and missing data. He closed by noting that 5 years from now, improved methods of analysis and the capability to store more data are likely to be available.

9. Discussion and Selection of Climate Change Scenarios for the Study

After lunch, the meeting participants spent several hours discussing and ultimately selecting a suite of climate change scenarios for the California impacts and adaptation studies. There were a number of implicit objectives in the discussion of scenarios. The objectives were to select a suite of scenarios that would:

▶ reflect a reasonable range of change in key parameters such as temperature and precipitation

▶ provide a full transient (i.e., at least the 2020s, 2060s, and 2090s) of results, or could be used to develop a transient scenario

▶ capture current spatial and temporal variability

▶ address changes in spatial and temporal variability to a feasible extent

▶ be made available quickly (i.e., based on completed and readily available climate model runs or transparent enough to be created easily)

▶ be readily used in impact assessments

▶ make up a reasonable number of scenarios (i.e., fit within budgets of the impact assessors).

The participants generally felt that scenarios reflecting plausible changes in day-to-day variability that could be caused by global warming would be desirable. The group, however, concluded that the estimated changes in daily variance from the GCMs are not reliable and that creating scenarios of change in daily variance is computationally difficult (e.g., a change in daily rainfall amounts must equal a change in total monthly rainfall coming from a GCM or another source). One option would be to use a weather generator, but doing so for the entire state of California would be challenging because the scenario would have to be spatially correlated between the generated outputs across grid points.

In contrast, it is computationally possible to generate scenarios of change in interannual climate. The problem is that not enough is known about changes in interannual variance to create meaningful scenarios. For example, although it is quite possible that climate change will increase the frequency and intensity of El Niños (e.g., Timmerman et al., 1999), El Niño events can be very different from each other. So it would be difficult to select El Niño characteristics to assume in future scenarios. Merely repeating a historical El Niño event, and changing temperature and precipitation, would not be realistic. Thus, it did not appear that the science is well enough advanced to enable us to create scenarios of climate variability for an area as large as California.

Creating scenarios of spatial variability also appeared desirable. RCMs would clearly be preferable to GCMs because they represent the major topographic features of California better than the GCMs. Unfortunately, there were not sufficient RCM results with which to develop a scenario. For example, RegCM2 has been run for only one decade, the 2040s. Insufficient time and computing resources were available in this study to run an RCM for a full transient simulation of the 21st century. As noted earlier, the impact modelers need transient scenarios for at least three decades (none of which happen to be the 2040s).

The group concluded that the only feasible options would be GCMs and incremental scenarios. GCMs have the advantage over incremental scenarios of providing some spatial and temporal variability as well as providing plausible changes in many meteorological variables. But they also involve a lot of data and can be complex to use. The group decided to select just two GCMs to limit the work that would be necessary to use GCMs in the impact analyses.

There is a consensus that California is likely to get wetter, particularly in the winter. However, there is still a significant possibility that there could be reduced precipitation (e.g., one-third of the GCMs surveyed by Dr. Wigley estimated a reduction in winter precipitation over California). The group decided it would be appropriate for the two GCMs to reflect these possibilities. Both the HadCM2 and the Canadian Centre for Climate (CCC) model (Flato et al., 2000) simulate wetter conditions in California in the winter. According to Dr. Wigley's analysis, the Hadley model does a better job of simulating current climate, so it was selected for the wet scenario. The

Parallel Climate Model (PCM)[5] was selected for the dry GCM scenario. NCAR performed the necessary downscaling for using the PCM in this effort.

The two GCMs alone gave a wide divergence in scenarios; the Hadley model estimated about a 65% increase in winter precipitation by 2100 and the PCM model about a 20% decrease. This would likely lead to broad differences in estimated impacts of climate change. But because the GCMs do not reflect a plausible intermediate range of climate change scenarios, the group decided to use incremental scenarios of changes in temperature and precipitation to reflect such an intermediate range. Three temperature change scenarios of 1.5°C, 3.0°C, and 5.0°C were selected, consistent with Mendelsohn and Neumann (1999).[6] Precipitation changes for these incremental scenarios were based on the average GCM outputs per degree of change in temperature as presented by Dr. Wigley. Co-varying temperature and precipitation reflects the relationship between these variables more realistically than does varying them independently. Two suites of precipitation scenarios were selected. One consists of no change in precipitation, which was combined with the three temperature changes. The no change in precipitation arises because the average change in summer precipitation across the GCMs is around zero. A second is an increase in precipitation of 6% per degree Celsius of warming in California climate, which corresponds with the average GCM change in winter precipitation per degree Celsius warming in California. It should be noted that these scenarios, summarized in Table 4, resulted in virtually no change in summer precipitation because current summer precipitation is very low.

Eight climate change scenarios were selected for the California project. Note that the HadCM2 model resulted in an approximate 100% increase in winter precipitation over southern California by 2100, and the PCM resulted in a 20% decrease in winter precipitation over southern California by 2100.

The +3°C, +18% scenario was considered the "central" scenario for analysis. This does not mean that it is most likely, but that the impact modelers should use it for evaluating the sensitivity of results to changes in nonclimate variables.

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5. Even though PCM was not included in the data Wigley presented to the workshop, it was selected because it produces reduced precipitation estimates for California and is a relatively new model from a reputable modeling center, NCAR.

6. The middle change in temperature of 3°C is consistent with a global average warming of 2.5°C, which is considered to be the most likely climate change percentage by 2100 (Wigley, 1999). On average, the GCMs showed that California will warm 14% more than the global average climate. Applying the 14% to a 2.5°C increase in global average temperature yielded an approximate 3°C increase in California temperature.

Table 4. California 2100 climate change scenarios for this assessment

GCM scenarios	Incremental scenarios	
	Temperature (°C)	Percent change in precipitation
HadCM2	1.5	0
PCM	1.5	9
	3	0
	3	18
	5	0
	5	30

The impact researchers also examined impacts in 2020 and 2060, for which two GCM scenarios and one incremental scenario were defined as specified in Table 5. The incremental was constructed assuming that change in temperature and precipitation between 2000 and 2100 would be linear. The GCM scenarios are an average of the three decades surrounding the 2020s and 2060s. The three decades were averaged because doing so smoothed out some of the interdecadal variance from the GCMs.

The scenarios were created by combining observations with scenario data. One of the simplest ways of doing this is to add a change in temperature to an observed temperature database and multiply a change in precipitation by an observed precipitation database. If the model or incremental scenario has a 3°C temperature increase, 3°C is added to all observed temperatures. If the model or incremental scenario has a 20% increase in precipitation, each amount of precipitation in each precipitation event in the observed database is increased by 20%. GCM results were downscaled to 100 km^2 using a method described in Attachment D. Note that in some applications, month by month results were used from the GCMs. This captures changes in intermonthly, interseasonal, and interannual variability as simulated by the GCMs.

Carbon dioxide concentrations are from Wigley (2000) and are shown in Table 6.

Table 5. Scenarios for 2020 and 2060

2020	
Incremental scenario	+0.6°C; +4% precipitation
HadCM2	Average annual change 2010-2039 +24.6%
PCM	Average annual change 2010-2039 -6.5%
2060	
Incremental scenario	+1.8°C; +11% precipitation
HadCM2	Average annual change 2050-2079 +32.0%
PCM	Average annual change 2050-2079 -11.7%

Table 6. Assumed CO$_2$ concentrations

Year	CO$_2$ concentrations (ppm)
2020	417
2060	543
2100	712

10. Conclusions and Future Analyses

The workshop considered the current state of climate change modeling as well as what is known about climate change for California. Global warming is likely to increase temperatures in the state, and all of the scenarios reflect that possibility.

It is likely, but not certain, that precipitation will increase, particularly in the winter. To reflect this, we selected a number of scenarios with increased precipitation, some with no change in precipitation, and one with reduced precipitation.

In the future, we expect regional climate models, statistical downscaling, and other techniques to be better developed so that they can be more readily used in studies such as this. These techniques offer much promise for better estimating changes in spatial variability, which is critical in a state such as California with highly diverse topography. It may require several years to develop these techniques for use in follow-on impact studies. California should consider developing climate scenarios now for immediate use in the improved regional climate models when they become available in the future.

In the future, we also hope that techniques will be better developed for generating plausible and internally consistent scenarios of changes in temporal variability. Scenarios of changes in climate variability might address such plausible events as increased ENSO intensity and changes in the persistence of storm tracks.

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Appendix I — Attachment A

Workshop Agenda for California Climate Scenarios Workshop

Agenda

Day 1 (Monday, 12 June 2000)

1:00 PM	Welcome Commissioners Robert Laurie and Arthur Rosenfeld
1:05 PM	Introductions, Meeting Objectives Guido Franco Tom Wilson Joel Smith
1:30 PM	What are the scenario data needs for the impacts modeling community? John Dracup Richard Howitt/Jay Lund Ron Neilson Rob Mendelsohn
2:30 PM	Current California climate, its determinants, trends, and data sources. Marlyn Shelton
3:15 PM	*Break*
3:30 PM	What are natural climate variabilities in California (ENSO, PDO, etc.) that are relevant for designing climate change scenarios for California for 2020, 2060, 2100? Dan Cayan
4:15 PM	What GCM data are available for California impacts modeling? Tom Wigley
5:00 PM	What RCM data are available for California impacts modeling? William Gutowski
5:45 PM	*Adjourn Day 1*

Day 2 (Tuesday, 13 June 2000)

8:30 AM	Current Activities & Plans in Statistical Downscaling of Climate, applied to California 　　　Tom Wigley
9:15 AM	Summary of the IPCC Third Assessment Report (Draft 2) Chapter 13 on Climate Scenario Development 　　　Chuck Hakkarinen
9:30 AM	What makes a good climate scenario? (variables, temporal and spatial scales, moments, measures and limits of uncertainties, etc.) 　　　Norm Miller
10:15 AM	*Break*
10:30 AM	Current Activities and Plans in Regional Climate Modeling of Climate, applied to California 　　　Lisa Sloan 　　　Dan Cayan 　　　Norm Miller
11:15 AM	Discussion on Current Activities and Plans in Regional Climate Modeling of Climate, applied to California
12:00 PM	*Lunch*

1:00 PM　　　　Round-table discussion on:

a)　　How do we insure we have a reasonably wide range of scenarios to reflect the plausible range of potential future climates in California?

b)　　How do we decide which model scenarios are most appropriate given the desire for selecting the "best" models and obtaining a wide range of scenarios?

c)　　What are the relative merits of using detailed model scenarios versus simplified "uniform or incremental change" scenarios? Is it necessary to use both to meet the goal of (a)?
　　　　　Moderator: Tom Wilson

2:30 PM   *Break*

2:45 PM   Group consensus on what scenarios to propose for use in these studies.

4:00 PM   *Adjourn Workshop*

Appendix I — Attachment B

Preliminary List of Workshop Attendees and Contact Information

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Appendix I — Attachment C
Communication from Stephen Schneider

From: Stephen H Schneider [shs@stanford.edu]
Sent: Saturday, June 10, 2000 12:58 AM
To: Norman Miller
Cc: 'CEC Climate Scenarios WS List'
Subject: Re: Climate Scenario?

Hello all. Sorry I can't attend your meeting — absurd travel schedule — but I wish you well in your work. Just a few comments if they may be helpful. I don't think the biggest problems with scenarios are really technical, but more in the area of how to make a reasonable set of SUBJECTIVE judgments over the likelihood of various components of scenarios, and of course, each scenario. To actually use them in an integrated assessment requires some sense of their probability — subjective of course since each is a counterfactual projection, but can be based on reasonable engineering, environmental, climatic, political, demographic components. Failure to attempt to characterize likelihoods, even in qualitative terms, simply defers that odious task to those less well equipped — decision makers who need to use them! I'm not happy that SRES ducked this problem, nor was the US review of it either. So if you can grapple at least with techniques to assess relative likelihoods — maybe all equally unlikely?? — that would be an interesting exercise. To help a bit I attach the Second Order Draft of Section 2.5 of the IPCC Working Group 2 report I was the lead author for since it discusses the uncertainties issue in somewhat formal terms and via literature review. I hope all this is useful.

Good luck, Steve

Appendix I — Attachment D

A Description of the Processes Involved in the Creation of Transient California Climate (US Albers, 10K x 10K grid resolution)

The transient California data climate used to run the MC1 model were produced from two sources: 1) the Vegetation Ecosystem Modeling and Analysis Project (VEMAP), and 2) the Parallel Climate Model (PCM). From VEMAP we had access to two GCM climate scenarios: 1) Hadley (HadCM2SUL) and the Canadian Climate Centre (CGCM1). From PCM we ran the B06.05 (historical 5) scenario and the B06.06 (business as usual 5) scenario. The processing of PCM and VEMAP climate proceeded along somewhat different paths resulting from differences in the nature of the input data (most notably, the difference in grid resolution). The description below will detail the common steps involved in processing the data, and will also describe the differences.

Table D.1 summarizes the spatial extent of the input data. The VEMAP data is at a much finer spatial resolution than the PCM data (though the HadCM2sul and cgcm1 scenarios themselves are interpolations of coarser grid GCM runs). The VEMAP data also is in sparse-grid format. That is, data are not available for all map-cells contained within the grid, but only for those map-cells that cover land area within the conterminous United States. The temporal resolution for both data-sources is monthly. VEMAP HadCM2SUL data goes from Jan. 1895 to Dec. 2099. VEMAP CGCM1 data goes from Jan. 1895 to Dec. 2100. PCM data goes from January 1960 to November 2099 with data missing for January and February 2000.

Table D.1. Geographic extent of starting datasets

	VEMAP (HadCM2sul and cgcm1)	PCM
Northern row (latitude)	48.75N	48.84N
Southern row (latitude)	25.25N	29.30N
Eastern column (longitude)	67.25W	112.5W
Western column (longitude)	124.25W	126.56W
Number of rows	48	8
Number of columns	115	6
Number of grid cells	3,261	48 (rows x columns)
Cell size (N-S)	0.5	2.79
Cell size (E-W)	0.5	2.81

Climate variables required by the MC1 vegetation model include precipitation (mm), mean monthly temperature (degrees C), mean monthly minimum temperature (degrees C), mean monthly maximum temperature (degrees C), mean monthly vapor pressure (pascals), and mean monthly wind speed (m/sec). All of these variables are directly available in the VEMAP datasets. For PCM, temperature and wind are directly available. Precipitation is available in m/s and specific humidity (kg/kg) functions as a surrogate for vapor pressure.

Step 1: Produce a Climatology

For both VEMAP scenarios and for PCM the first step required was the production of a climatology (mean 30 year climate for 1961-1990). The process for this was the same for all scenarios and all climate variables. For each month the mean was calculated for the 30 years, i.e., the January value was calculated as the mean of January values for 1961-1990, February is the mean of 1961-1990 February values, etc. The climatology produced is at the same scale as the original transient climate.

Step 2: Calculate Climate Anomalies

Difference anomalies were calculated for mean, minimum, and maximum temperatures. Ratio anomalies were calculated for vapor pressure and precipitation. Anomalies were calculated by comparing the value for any variable each month from the transient climate to the value for the corresponding month in the climatology. For example: to calculate the temperature anomaly for January 1994, the mean January temperature for 1961-1990 was subtracted from the January 1994 temperature. To calculate the precipitation anomaly for January 1994, the January 1994 precipitation value was divided by the mean January precipitation value for 1961-1990. Ratio anomalies were capped at a value of 5.0. In those rare cases where the climatological precipitation is equal to zero, the ratio was set to 1.0 if the transient precipitation is also 0, and was set to the maximum (5.0) if the transient precipitation is anything greater than 0. The results of this step are climate anomaly files at the same spatial and temporal resolution as the original climate files.

We noted before that the precipitation and water vapor variables available for PCM are not exactly the same as those used by the MC1 vegetation model. PCM precipitation comes in units of m/sec whereas MC1 needs precipitation input in units of mm/month. PCM water vapor data comes as specific humidity (kg/kg) whereas MC1 requires vapor pressure in units of pascals. Because in both cases the relationship between the desired and the available climate variable is linear, the ratio anomaly calculated from the PCM variable was used for subsequent calculations of precipitation and vapor pressure. No attempt was made to translate the PCM precipitation and specific humidity values prior to calculating the ratio anomalies.

Steps 3 and 4: Interpolate and Reproject the Climate Anomalies

The anomalies now needed to be translated to the US Albers 10K x 10K resolution. Descriptions of the geographic extent of the target grid are shown in Table D.2. Parameters describing the Albers projection are shown in Table D.3. For the VEMAP data the difference between the spatial resolution of the source and target grids is relatively small. The reprojection and interpolation were done in a single step using the IPW software (function "reproj") and accepting the default nearest-neighbor resampling method.

For the PCM data the difference between the spatial resolution of the source and target grids is relatively large, and therefore the interpolation and reprojection were conducted separately. For the interpolation, a Delaunay triangulation was performed on the dataset. From the triangulated data a quintic polynomial interpolation was performed. The Quintic polynomial interpolation used is based on Akima's quintic polynomials from "A Method of Bivariate Interpolation and Smooth Surface Fitting for Irregularly Distributed Data Points" in ACM Transactions on Mathematical Software, 4, 148-159. Derivatives are estimated by Renka's global method in "A Triangle-Based C1 Interpolation Method" in Rocky Mountain Journal of Mathematics, vol. 14, no. 1, 1984. The triangulation and interpolation were performed using the IDL software (functions TRIANGULATE and TRIGRID). The interpolation resulted in a latitude/longitude grid of climate anomalies at a higher spatial resolution than the source data. Table D.4 describes the interpolated grid. This grid is roughly at a 10 km x 10 km spatial resolution (though the grid is not equal-area). The reprojection of the PCM data is performed in the same manner as for the VEMAP data using the IPW software (function "reproj") and accepting the default nearest-neighbor resampling method.

Table D.2. Geographic extent of target dataset

Northern row (meters)	2,480,000
Southern row (meters)	1,200,000
Eastern column (meters)	-1,620,000
Western column (meters)	-2,370,000
Number of rows	128
Number of columns	75
Number of grid cells	4,092
Cell size (N-S)	10,000
Cell size (E-W)	10,000

Table D.3. Parameters for the U.S. Albers projection and datum

First standard parallel	29.5
Second standard parallel	45.5
Central meridian	-96.0
Latitude of projection's origin	23.0
Datum	WGS72

Table D.4. Geographic extent of intermediate PCM grid

Northern row (latitude)	42.0667 N
Southern row (latitude)	32.4667 N
Eastern column (longitude)	113.9333 W
Western column (longitude)	124.5333 W
Cell size (N-S)	0.0667
Cell size (E-W)	0.0667

Step 5: Apply the Anomalies to the 10K Climatology

The last step was to apply the 10K anomaly data to the 10K climatology. Difference anomalies were added and ratio anomalies were multiplied. The output 10K transient climate was then stored in NetCDF format.